Coupling of light from an optical fiber taper into silver nanowires

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We report the coupling of photons from an optical fiber taper to surface plasmon modes of silver nanowires. The launch of propagating plasmons can be realized not only at ends of the nanowires, but also at the midsection. The degree of the coupling can be controlled by adjusting the light polarization. In addition, we present the coupling of light into multiple nanowires from a single optical fiber taper simultaneously. Our demonstration offers a novel method for optimizing plasmon coupling into nanoscale metallic waveguides and promotes the realization of highly integrated plasmonic devices.

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With the increasing attention and progress of nanotechnology, the dimensions of ultrafast transistors are on the order of 50 nm. The imperative problem now is carrying digital information from one end to the other end of a microprocessor if we want to increase the speed of microprocessors. Optical interconnects such as fiber optic cables can carry digital data with a capacity 1000 times more than that of electronic interconnects, while fiber optic cables are larger due to the optical diffraction limit. This size-compatibility problem may be solved if the optical elements can be integrated on chip and fabricated at nanoscale. One such proposal is surface plasmons, which are electromagnetic waves that propagate along the surface of a conductor[1]. Plasmonics, surface plasmon-based optics, have been demonstrated and investigated intensively in nanoscale metallic hole arrays[2, 3, 4], metallic waveguides[5, 6, 7], and metallic nanowires[8, 9, 10, 11, 12, 13] in recent years. Among the different kinds of plasmonic waveguides, sliver nanowires have some unique properties that make them particularly attractive, such as low propagating loss due to their smooth surface and scattering of plasmons to photons only at their sharp ends. Since the momentums of the photons and plasmons are different, it is a challenge to couple light into plasmon waveguides efficiently. The general methods for plasmon excitation include prism coupling and focusing of light onto one end of the nanowire with a microscope objective. Nanoparticle antenna-based approach is also proved to be an efficient way for optimizing plasmon coupling into nanowires[12], which allows for direct coupling into straight, continuous nanowires by using a nanoparticle as an antenna. Recently, a single polymer waveguide is used to couple light into multiple nanowires simultaneously[13] as well, aiming at providing light to a number of nanoscale devices in the future integrated photonic circuits. Whereas due to the random distribution of nanowires and nanoparticles, it is hard to achieve optimum coupling efficiency for the two methods under present technology.

Here we report a new experimental method to couple light with plasmons in sliver nanowires by using an optical single mode fiber taper contacting one or several nanowires. It is found that the plasmons can be excited from the midsection of a continuous, smooth nanowire. Using a fiber taper, we can couple light into a nanowire from any position of it. Moreover, the fiber taper can be used to arrange the position of the nanowires, and several nanowires can be excited simultaneously by one fiber taper. This structure bridges the classical optical fibers and the nanoscale plasmonic nanowires and might be useful for coupling light to nanophotonic devices in integrated circuits.

There are a lot of methods for the controlled synthesis of silver narowires[14, 15, 16]. Here a solvothermal process is used to fabricate silver nanowires. In a typical synthesis procedure, 2 mmol of PVP and 1.4 mmol of $AgNO_3$ were successively dissolved in 36 mL of ethylene glycol. Then 2 mL of NaCl ethylene glycol solution (1.2 mmol/L) and 2 mL of ferric nitrate ethylene glycol solution (15 mmol/L) were added under magnetic stirring. The mixture was sealed in a 50 mL autoclave and heated in oven at 180 $^{\circ}C$ for 12 hours. Finally, the Teflon-lined autoclave was cooled naturally to room temperature, and the final products were obtained after centrifugation of the straw yellow suspension and washed with deionized water and ethanol for several times (centrifugal speed is 6000 r/min). The products were preserved in ethanol. The as-synthesized products were characterized by field emission scanning electron microscopy (FE-SEM; Hitachi, S-4800)

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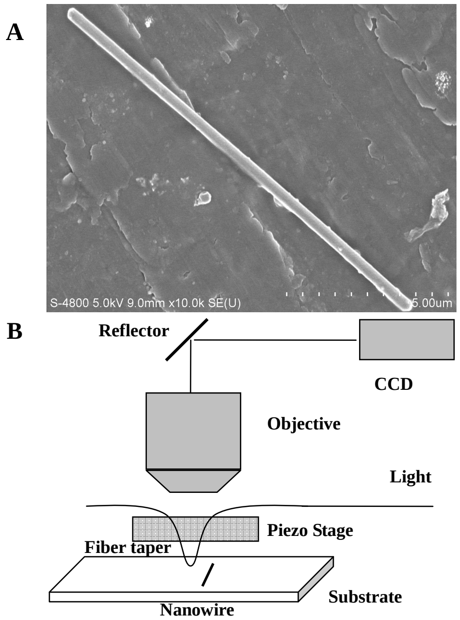

FIG. 1: (A)Scanning electron micrographs of a 14 μm long silver nanowire. Its diameter is about 300 nm. (B)Sketch map of our experiment setup. Laser beam with 780 nm wavelength is coupled into an optical fiber taper which is contacted with nanowires. The fiber taper is mounted in a U-shaped configuration and moved by a piezo-electric stage. Scattering light is recorded by a CCD camera after a microscope objective.

at an acceleration voltage of 5.0 kV. The wires obtained here have a diameter about 300 nm and lengths about 10 μm(Fig. 1A).

Samples used in our experiment were prepared by drop-casting a dilute nanowires suspension on cover glass and then letting them dry in the open air. A tapered fiber was prepared from a single mode fiber at a wavelength of 780 nm (Newport) which was heated by a Hydrogen microtorch and stretched to the opposite directions with two translators[17, 18]. The curvature of the taper profile was small to realize adiabatic propagation of light through the tapered region. In our experiment, the fiber taper reached a minimum diameter of only about 1 μm which had evanescent fields outside[19]. Laser beam with 780 nm wavelength was coupled into the optical fiber and laser polarization was controlled by a polarization beam splitter (PBS) followed by a half wave plate (HWP)[20]. Rotating the HWP allowed us to investigate the relationship between the coupling efficiency and the polarization of light. The optical fiber taper was placed above and parallel to the substrate where nanowires were dropped. It was mounted in a U-shaped configuration and moved by a three dimensional piezo-electric stage (Physik Instrumente Co., Ltd. NanoCube XYZ Piezo Stage), sketched in Fig. 1B. Scattering light from the nanowire was recorded by a CCD camera after a microscope objective.

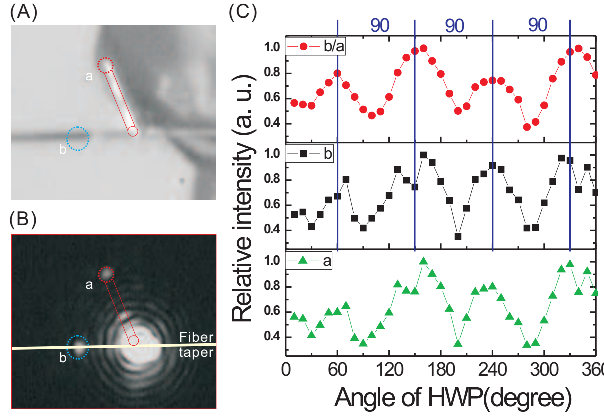

FIG. 2: Polarization dependence of coupling efficiency at nanowire end. (A) Micrograph of a nanowire contacted with a fiber taper at one end. (B) Emission can be observed from the other end. (C) Far-field emission intensities as a function of laser polarization angle. a is the emission intensity determined by averaging the four brightest pixels at site "a" and b is the intensity of site "b" which is used as a reference of background scattering since there is a dust adhering to the fiber taper. a/b gives the relationship between the coupling strength and the polarization of light.

To eliminate the influence of the glass surface, we put a nanowire on the edge as shown in Figure 2A. The length of the nanowire was about 11 μm. The fiber taper contacted the nanowire at one end and the emission was observed from the other end clearly, which verified that optical fiber taper could also excite surface plasmons in metallic nanowires and couple optical information into nanoscale devices. The coupling strength was measured by changing the polarization of the input light. For each polarization, the emission intensity was determined by averaging the four brightest pixels at site "a"(see inset of Fig. 2). Intensity of site "b" was used as a reference of background scattering since there was a dust adhering to the fiber taper. It changed with the polarization of the input light for the different coupling efficiencies. Fig. 2C showed the relationship between the coupling strength and the polarization of light. The far-field emission curve as a function of polarization angle was approximately in accord with the theoretical prediction(cosine or sine function)[11, 12], and the error here might come from the strong background scattering. This phenomenon was similar with the case that we excited surface plasmons with focused laser spot in free space using a 100x microscope objective.

As we know, the momentum of the propagating plasmon(k_{sp}) is larger than that of the incoming photon(k_{ph}), so there needs an additional wavevector(Δk) to sustain the momentum conservation condition. Surface plasmons in nanowires can be excited where the symmetry is broken, for example, at the ends and sharp bends[8, 9, 10, 11], because an extra wavevec-

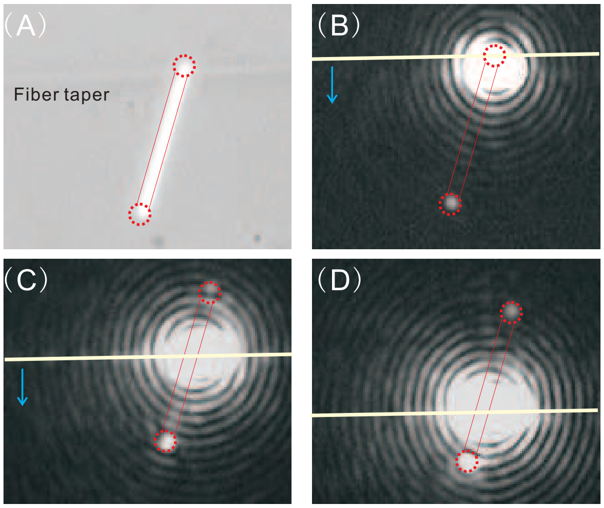

FIG. 3: Plasmons are observed from both ends by contacting the fiber taper with a nanowire in the midsection. (A) Micrograph of a nanowire contacted with a fiber taper. (B),(C),(D) The fiber taper contact the nanowire with different sections and scattering light from both ends are detected.

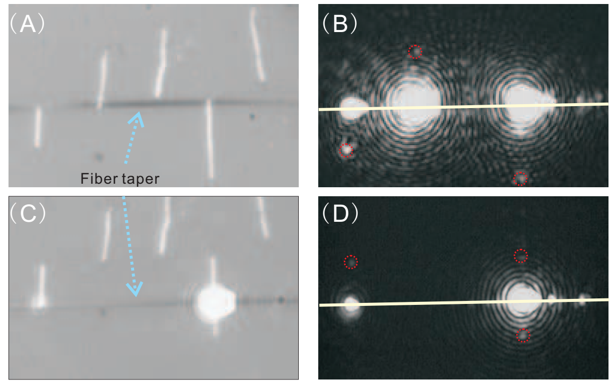

FIG. 4: Coupling of light into multiple nanowires from a single optical fiber taper. (A) A micrograph with white light illumination shows a fiber taper contacted with three nanowires simultaneously. (B) Light scattered from the ends of the three nanowires can be observed. (C) A fiber taper contacted with a nanowire at end and another nanowire at midsection. (D) Dark filed picture of (C) indicates that we can excite surface plasmons selectively from end of a nanowire or its midsection.

tor ($\Delta k_{scatter}$) is supplied according to the scattering mechanism in this situation. Surface plasmons can not be excited in the midsection directly, as a result of the smooth surface of the nanowire. Since the plasmonic waveguides may be very long in practice like optical fiber, it will be more convenient if we can couple light into them from the midsection. One scheme to directly couple light into straight, continuous nanowires is using a nanoparticle as an antenna[12]. However this method may be not expedient if we want to couple light at random sections of a nanowire since the distributions of nanowires and nanoparticles can not be controlled easily.

From Fig. 3, we can see that plasmons were observed from both ends by contacting the fiber taper with a nanowire in its midsection. The fiber taper was also moved from one end to the other end of this nanowire slowly, and scattering light was observed as periodic glint during this process. To testify that it was not the result of the exceptive discontinuity of the nanowire, we focused the laser light on the midsection using a 100X microscope objective and no plasmon was launched. Several other nanowires were tested subsequently as well and gave the similar phenomena. The reason for direct coupling in midsection may be that the symmetry of the nanowire is disrupted when the fiber taper and the nanowire are contacted with each other. An additional momentum is offered partly by scattering on the nanowire surface and else from the evanescent optical field of the fiber taper. Moving the optical fiber taper by the stage randomly, we can launch plasmons from any section of a straight nanowire. Similar to the case of exciting plasmon from the ends, coupling strength can be modulated by the light polarization. To check whether the continuities of the nanowires were damaged after contacted with fiber taper, we used the free space coupling method and proved that the whole process of coupling light from fiber taper to surface plasmons was safe for nanowires and exercisable in practice. It should be noticed that the intensity of output light from two ends changed with coupling positions. A potential explanation is that the silver nanowire can work as an efficient Fabry-Perot resonator, in which the scattered light intensity is modulated as a function of coupling position with the distinct Fabry-Perot resonator modes. Further investigation is necessary to give a numerical analysis which is beyond this work. According to the free coupling property of this protocol, it is especially useful for coupling light into nanodevices which have no sharp end, such as nanoring[21, 22].

Besides the benefit of coupling light from any sections of nanowires, another advantage of the fiber taper coupling method is that we can excite surface plasmons in many nanowires simultaneously using a single fiber taper. In the future plasmonic circuits, we may need to integrate many nano-waveguides to increase data transmission rates and capacity. Obviously, the previous methods of prism coupling and focusing with microscope objective are not convenient and can not be applied on chips. Pyayt and his coworkers proposed to excite plasmons in many nanowires by putting them perpendicular to a polymer waveguide with one end located close to the light inside the waveguide[13]. In their structure, the sliver nanowires were oriented randomly on the substrate and a series of SU-8 stripes were covered on them as polymer waveguides. They observed that the light coupled in the waveguide could propagate along several nanowires simultaneously. While due to the random distribution of nanowires, many of them did not couple light out of the

waveguide. Precise control of nanowire orientation was essential to achieve optimum coupling efficiency. Here, we used the fiber taper to substitute for the waveguide and discovered the similar phenomenon while the whole process can be controlled more precisely.

We utilized a broken fiber taper to adhibit a nanowire, then moved it to the appropriate place carefully by a nanoscale piezo stage and put it down on the substrate. Repeating this process several times, we got a well organized distribution of nanowires. Though some of the nanowires might be destroyed during this operation, we can clear the bad ones and keep the good ones. In this work, five nanowires were placed parallel to each other on the substrate as shown in Fig. 4A. A fiber taper contacted three of them simultaneously on their ends. We could see that light scattered from the other ends of these three nanowires at the same time and the two uncontacted nanowires remained dark, as shown in Fig. 4B. Likewise, we can excite surface plasmons selectively from end of a nanowire or its midsection. This proved that our method can be used to couple laser light to multiple nanowires simultaneously.

In summary, we have demonstrated an original technique to couple light into silver nanowires. The new method has two remarkable advantages: One is that plasmons can be launched from any part of a nanowire, and the other is that one optical fiber taper can be applied to couple light into many nanowires simultaneously. This method can directly combine the classical optical elements with the nanoscale plasmonic devices, and thus may be practical for optical input of nanoscale photonic devices in highly integrated circuits.

Acknowledgments

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